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AN IMMERSED FIELD CLUSTER KLYSTRON*

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R. B. PALMER
Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94309, USA; and
Brookhaven National Laboratory, Upton, NY 11973, USA
and
W. B. HERRMANNSFELDT and K. R. EPPLEY
Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94309, USA

Abstract Future linear colliders have a need for high power, high frequency, and short-pulse radio frequency sources. The proposed "cluster klystron" should give over 1 GW of 12 GHz radio frequency power, can employ direct current or a long high-voltage pulse, but can be gated to give pulses down to a few tens of nanoseconds. The device consists of 42 parallel 100 A channels. Each channel is fed from an individual magnetron-type gun employing a common 50 kV mod-anode. The beams are accelerated to 400 kV in common dc accelerating gaps and fed into the 42 separate klystron channels. Focusing of all channels is achieved by a single overall 4 kG magnetic field. Simulations of expected performance suggest that the efficiency could be above 70%.

INTRODUCTION

For the TeV Linear Collider (TLC), we require approximately 1 GW/m, in 70 nsec pulses of 11.4 GHz RF power. With three stages of RF Binary Pulse Compression[1] (BPC), this is reduced to about 1 GW every 6 m in about 600 nsec pulses, including an allowance for reasonable efficiency for the BPC. We propose here a program to develop a cluster klystron that should meet these requirements with good efficiency and reasonable cost.

Each unit would consist of a cluster of about 42 individual klystron channels, each delivering at least 26 MW at about 70% efficiency. The power per unit would thus be at least 1 GW. The 42 tubes would be enclosed in a single 4–5 kG focusing solenoid covering both the tubes and the electron guns. All outputs would be merged into a single waveguide.

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The electron beams would be provided by small, magnetron injection guns similar to the type used for gyrotrons, except that the magnetic field would be constant. The cross-field design allows for high surface fields on the cathode so that unusually high current density can be emitted. A new type of reservoir cathode, developed by Varian Associates, would be used to deliver about 40 A/cm^2. The beam would be switched by pulsing the magnetron gun anode to 40–50 kV, thus providing short, square output pulses. Acceleration to 400 kV would occur in a subsequent gap or gaps, using a relatively long pulse modulator or dc power. A high voltage cable would be used as the pulse forming network. The pulse length would depend on the number of BPC stages, which could be between zero and four stages. The cost and efficiency trade-offs between longer pulses, with fewer klystrons and more pulse compression, as compared with more klystrons and shorter pulses without the complexities of multiple BPC stages, will be made after better cost data is available.

PROGRESS IN DESIGN STUDIES

History

The concept of a cluster klystron was first proposed by a group from General Electric.[2] A real, ten-beam device using solenoidal magnetic focusing was built and tested, and the problems of coupling the multiple channels were studied. They concluded that resonant coupling of between 40 and 100 tubes should not be a problem. They noted, for instance that in their ten-tube device, if one tube failed completely, the output power dropped by only 15%; i.e., only 5% extra loss due to the resulting imbalance of the remaining nine tubes. At Snowmass 1988, Palmer and Miller reinvented this magnetically focused cluster klystron,[3] the only difference being in the method of coupling between cavities. In both cases, Pierce guns were employed and an iron plate with holes was used to shield the klystron focusing field from the gun region.

The main problems in the above proposals arose from the use of a Pierce gun. These guns require almost no field at the cathode and thus need the iron plate to shield the klystron focusing field from the cathode. The use of the iron plate is inconvenient and imposes limits on the focusing field, and thus on the number of tubes that could be enclosed. The Pierce guns also require significant lateral space for the cathode and field shaping electrodes, thus limiting the number of tubes that

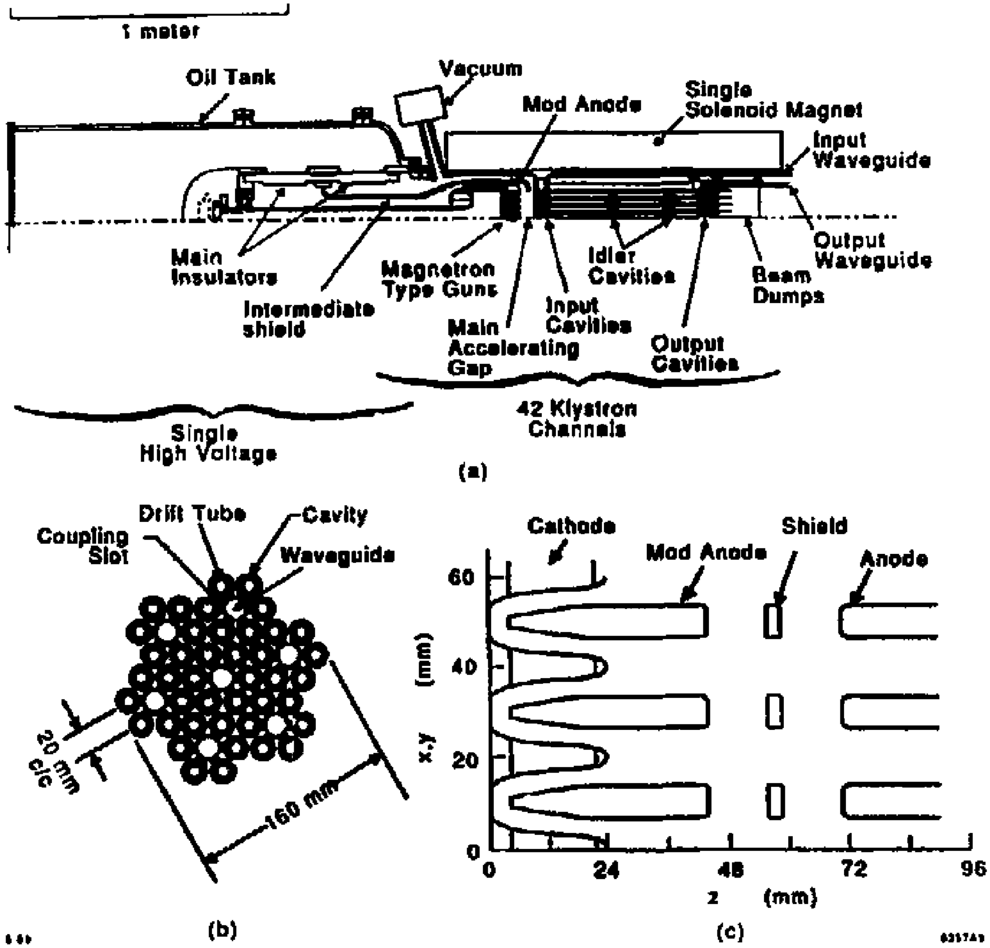

FIGURE 1 Conceptual design of an immersed field cluster klystron: (a) longitudinal cross section of complete tube including high voltage tank (SLAC lasertron design); (b) possible cross section of 42 individual klystron cavities; (c) enlarged view of three magnetron-type guns.

can be packed in a given area. A. Maschke, as a variation on his proposal to build an electrostatically focused multibeam accelerator,[4] also proposed an electrostatically focused multibeam klystron, but this was not seriously studied. It appears that significant currents can only be focused with very high electric fields. When magnetic focusing is used, the multibeam klystron may yet be the best solution at very high frequencies

The present proposal differs from these others in using magnetron-type guns.[5] These guns use a long conical cathode within a conical anode, both immersed in an axial magnetic field that can be the same as that focusing the klystrons. No iron plate is now needed. In addition, the guns have no more lateral extent than the klystron cavities and can be packed very close to one another, as shown in Fig. 1. The concept of using a hollow-beam gun of this type was suggested earlier by Chodorow,[6] who noted that very high perveance can be obtained and that the hollow beam can aid the beam transport and efficiency of the resulting klystron.

Gun Design

The gun discussed in Ref. (5) was space-charge limited, and employed an elegant balance of the space-charge and focusing forces to generate a low emittance beam with essentially no scalloping. In our early EGUN[7] studies of a scaled design we were unable to reproduce this condition. We did, however, find temperature-limited solutions that give acceptable emittance. Figure 2 shows the calculated trajectories for the solution that has been used in the subsequent klystron calculations. Its characteristics are shown in Table I.

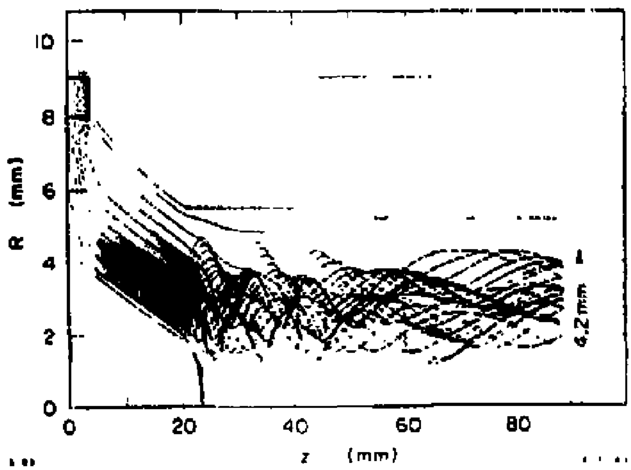

FIGURE 2 A trace of trajectories through the magnetron-type gun, from the program EGUN (note the unequal horizontal and vertical scales).

Further gun design studies are underway in collaboration with consultants and it is hoped that space-charge limited solutions will be found with lower emittance and possibly larger area reduction factors. We may, however, prefer to remain with a temperature-limited solution since this should provide a greater cathode lifetime for a given current density (see below).

TABLE I Gun characteristics.

Parameter	Value
Total beam current	100 A
Beam, outer radius	4.2 mm
Beam, inner radius	2.0 mm
Cathode, current density	36 A/cm^2
Cathode, max radius	3.6 mm
Cathode, min radius	1.8 mm
Cathode length	16.4 mm
Area reduction factor	6.5
Focu sing field	4.0 kG
Mod anode voltage	50 kV
Mod anode gap	3.5 mm
Radial gun field	200 kV/cm
Main anode voltage	400 kV
Main anode gaps	2 × 4 cm
Accelerating field	50 kV/cm

Klystron Design

The perveance of each tube (at 100 A and 400 kV) is only 0.4 micropervs, and with this a klystron efficiency of at least 65% should be expected (as shown in Fig. 3) which is a compilation of results from Thomson CSF.[8] The hollow beam should further help, but the higher emittance will hurt.

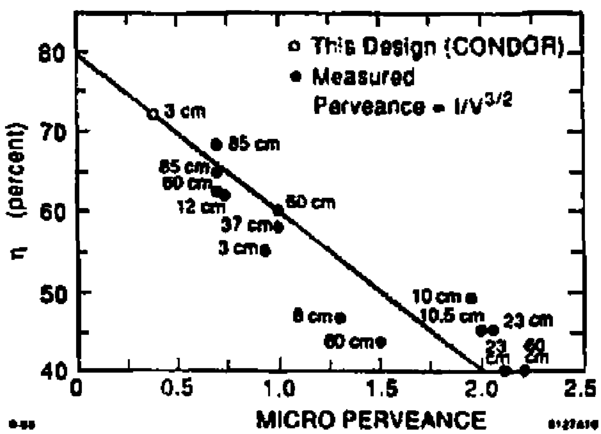

FIGURE 3 Measured efficiencies of various klystrons as a function of perveance, together with efficiency for this tube as calculated by CONDOR.

TABLE II Klystron parameters.

Parameter	Value
Frequency	11.4 GHz
Drift tube radius	5.0 mm
Number of cavities	6
Beam current	100 A
Beam voltage	400 kV
Perveance	0.4 micropervs
Focus field	4 kG
RF drive power	16 kW
Kinematic efficiency	74%
Total RF efficiency	0%
Average efficiency	72%

Cavities	1	2	3	4	5	6
Cavity positions (cm)	0.0	25.0	38.5	47.0	49	49.5
Gap width (mm)	3.3	3.3	3.3	3.3	3.3	2.0
Gap voltages (kV)	30	60	120	240	300	150
Phase (degrees)		−1.35	−1.37	−0.57	−0.33	0.4
Power out (MW)		0.3	1.03	12.5	10.9	2.8

Results of a study made by using CONDOR,[9]—a two-dimensional particle-in-cell code—are shown in Table II and illustrated in fig. 4. A relatively conventional design with two bunching cavities and two outputs gave an efficiency of approximately 63%. A more complicated multicavity design with three bunching cavities and three output cavities shown in Fig. 5, gave a predicted efficiency of 72% (this being the average of a kinematic efficiency of 70% and a power efficiency of 74%). Since the cost of multiple cavities is likely to be a very small fraction of the total cluster klystron cost, it seems reasonable to further explore such high-efficiency designs.

Cathode Considerations

In order to obtain the required 100 A in the beam, a cathode current density of nearly 40 A/cm^2 was required. We have learned from Varian[10] that with a good osmium dispenser cathode, 40 A/cm^2 would require a temperature of 1100°C, if space charge limited, but only 1070°C if, as is the case here, the applied voltage is twice that needed for the space charge limit [see Fig. 5(a)]. But even in this case, with conventional cathodes, the lifetime is less than 2000 hrs [Fig. 5(b)].

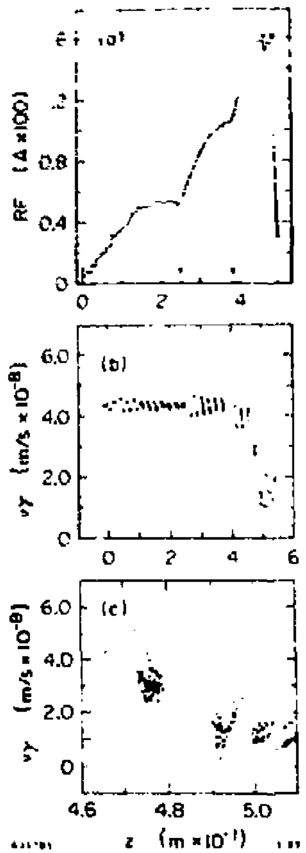

FIGURE 4 CONDOR output for this klystron design: (a) RF current as a function of length along the tube; The arrows in the figure denote the locations of RF cavities. (b) Phase diagram: particle momentum ($v \times \gamma$) as a function of position along the tube at a particular instant of time. (c) Phase diagram for the region of the output cavities.

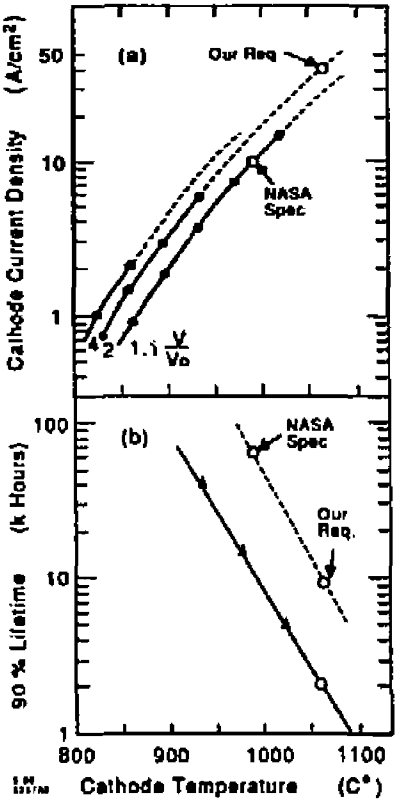

FIGURE 5 Performance of Varian cathodes [Ref. (10)]: (a) Current density as a function of temperature for differing applied voltages V/V_0; where V_0 is the voltage to achieve the space charge limit at that current, and (b) Lifetime of cathodes as a function of temperature; continuous line is for present technology; broken line is for the new reservoir technology being developed for a NASA specification. Open dot on the solid line shows expected lifetime at our current density using present technology.

Again we have learned from Varian[10] that, for such cathodes at a given temperature, the life is limited more or less equally by:

1) the loss of active chemicals within the porous tungsten matrix that are generating the active barium oxide, and
2) the diffusion of the tungsten into the osmium surface layer causing a loss in its special role of supporting the monolayer of barium oxide in the correct polarized state.

Varian now believes they have solutions to both limits: the barium oxide is generated from a reservoir external to the cathode surface and a special proprietary barrier is used to stop the tungsten diffusion. With these improvements they believe that a cathode operating at 1070°C should have a lifetime of about 15,000 hrs, which should be sufficient.

If such currents are not available, then the power per tube would be less and either more tubes, more binary pulse compression, or less accelerating gradient (e.g., for an intermediate linear collider) could be employed, but there would in this case be problems in the klystron design since the low absolute currents per channel would require higher Q's to obtain the required cavity voltages. These higher Q's would lower the time response which must be short compared to the final pulse length in order for the binary pulse compression system to be sufficiently efficient. Because cathode performance is so critical to the prospects for the cluster klystron concept, we have initiated discussions with Varian Associates, with the objective of arranging for an industrial collaborator for cathode development.

Clustering Concepts

In Ref. (2), the ten tubes were arranged in a linear array, and operated with 180° phase advance between tubes. There were, however, dummy cavities introduced between adjacent tubes so that the effective phase advance was 90°, the spacing between modes was maximum, and the group velocity large. With this arrangement they concluded that between 40 and 100 cavities could be coupled without exciting unwanted modes. In Ref. (3), it was proposed to arrange the tubes in several semiindependent, hexagonal, flower-like patterns, each with its own input and output waveguides; the power in each of the guides being subsequently merged in a multiple hybrid. More study of possible arrangements is now underway and the best arrangement is unlikely to be either of the above.

Electrical Considerations

In the case of the SLC, the power supplies and modulators cost significantly more than the klystrons they drive (about $200,000 compared with about $70,000). A similar situation seems to hold in the case of "two-beam accelerators," whether the primary beam is accelerated by induction units or superconducting cavities. In either case a major, if not dominant cost, is the energy storage compressor and the induction ferrite in the first case, or the superconducting cavities in the second.

It is therefore an important feature of the present proposal that the first anode can be modulated. In this case, the required electrical energy can be stored on a low-cost, high-voltage delay line (a high-voltage cable), and switched into the klystron by pulsing this mod anode. In effect, the klystron becomes its own hard-tube modulator. The costs of the required dc power supplies and high-voltage cable had been estimated by Lasertron groups, and are much lower than those for modulators, magnetic compressors or superconducting cavities. The breakdown problems experienced by various Lasertron groups are unlikely to be repeated here since (a) cesium will not be injected into the vacuum, (b) the accelerating fields are more than a factor of two less, and (c) there is magnetic shielding radially.

The impedance Z_k presented to the high voltage line by the cluster klystron would be 400,000 V / 4,200 A = 95 Ω. If the line impedance is Z_0, then the required initial (V_1) and final (V_2) line voltages are

$$V_1 = V_k \left(1 + \frac{Z_0}{Z_k}\right) \quad ,$$

$$V_2 = V_k \left(1 - \frac{Z_0}{Z_k}\right) \quad .$$

It is clearly desirable to keep V_1 low, thus requiring a low line impedance, but this implies a large initial stored energy U_1:

$$U_1 = \frac{U_k}{4} \frac{Z_k}{Z_0} \left(1 + \frac{Z_0}{/Z_k}\right)^2 \quad .$$

A reasonable compromise might be the set of parameters shown in Table III. For the data in the table, we assume the final pulse of 600 ns, as earlier discussed. Allowing for a 30 ns risetime, the pulse length τ needed is 630 ns. The length (l) of high-voltage line needed is given by

$$l = \tau \cdot \frac{c}{\sqrt{\epsilon}} \quad ,$$

where $\epsilon = 2.25$ is the relative dielectric constant for polyethylene dielectrics.

TABLE III Electrical parameters.

Parameter	Symbol	Value
Pulse length	τ	630 ns
Cable length	l	63 m
Cable impedance	Z_0	24 Ω
Initial voltage	U_1	500 kV
Final voltage	U_2	300 kV
Klystron energy	U_k	1000 J
Initial stored energy	U_1	1560 J
Final stored energy	U_2	560 J

The lower voltage would be left on the tube for most of the time between pulses, with a short charging time before the next pulse [Fig. 6(b)]

An alternative method of charging the line would be to use a slow modulator with energy recovery. This would avoid leaving high voltage on the tube between pulses, but is almost certainly more expensive and less efficient.

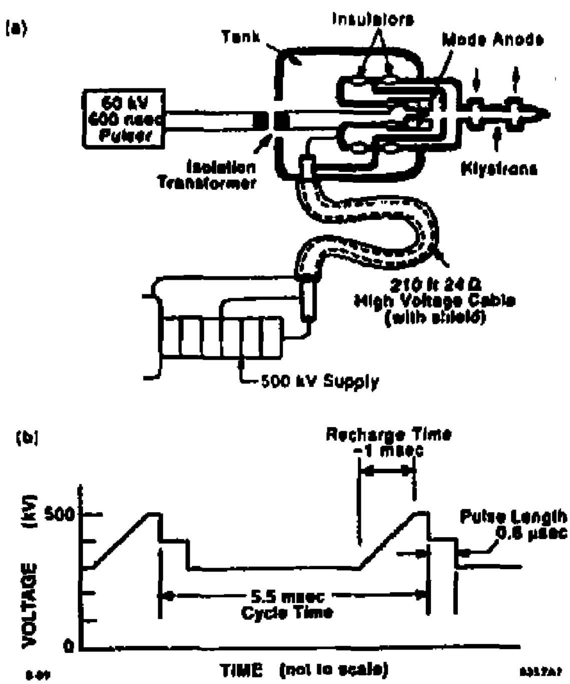

FIGURE 6 Electrical system: (a) Circuit diagram. (b) Klystron voltage vs. time.

The mod anode would have a capacity of about 80 pF and, ignoring beam loading, would require about 50 kV from a pulser delivering ~ 100 mJ in about 30 nsec, i.e., ~ 130 A. The beam loading effects of turning on a 4 kA beam in this time adds about 50% to this need to about 200 A. The pulser could, in principle, be mounted at high voltage inside the cathode housing, but it would probably be more convenient to have it external and use an isolation transformer, as shown in Fig. 6(a).

Magnet Design

The magnet must provide a field sufficiently uniform to assure that each beam is focused along its own drift tube. Since these tubes are only 1 cm diameter and the beam nearly fills them, the beams need to be steered to an accuracy of about 0.2 mm. Given 2 cm center-to-center beam spacing, the required good field region is approximately 18 cm diam and 65 cm long. To maintain the field lines straight to 0.5 mm within this volume, the field must be constant to about 0.4%. The magnet bore must be considerably bigger than the klystrons themselves in order to accommodate the high voltage gun (Fig. 1), and will have to be significantly longer than the klystrons in order to achieve the required field uniformity. Possible magnet parameters are shown in Table IV.

TABLE IV Magnet parameters.

Parameter	Value
Magnetic Field	4.5 kG
Overall length	120 cm
Inside diameter	35 cm
Field length	65 cm
Field diameter	18 cm
Field quality	0.4%

It is probable that for the 1000 units required for a linear collider the most economical magnet would be superconducting, but initial tests would be done with conventional magnets. As an existence proof, we have designed a conventional coil solenoid that fulfills the above size and field requirements with currents of between 400 500 A/cm.[2]

SUMMARY

Initial studies of a cluster klystron are encouraging and suggest that a source could be built for reasonable cost with the specifications shown in Table V.

TABLE V Summary parameters.

Parameter	Value
Frequency	11.4 GHz
Total output power	1.2 GW
Efficiency	70 %
Rise time	30 ns
Number of tubes	42
Power per tube	28 MW
Current per tube	100 A
Voltage	400 kV
Perveance	0.4 micropervs
Magnetic field	4–5 kG
Modulating anode	40 kV
Cathode current density	40 A/cm^2

Of these specifications, only the cathode current (with reasonable lifetime) requires a real extrapolation from what has been demonstrated. For the rest, they represent new configurations of a number of existing technologies. A cluster klystron with 10 tubes has been built and worked well; the extrapolation to 42 can certainly be accomplished by combing outputs with hybrids. An efficiency of 70% has been achieved in klystrons with the specified perveance. A magnetron gun klystron has been built and worked well. A dc 400 kV gun with high voltage cable energy storage, has been built and held voltage (prior to the introduction of cesium).

Much work requires to be done, but we are encouraged to believe that this is a good candidate for a linear collider power source.

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